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Transverse lepton polarization in polarized W decays

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Calculations of the transverse polarization of leptons in the decay $W \to l\nu$ with polarized W's are presented. Planned accelerators will produce enough W's for observation of the standard model contributions to this polarization. One loop corrections to the polarization are given; these are too small to be seen at presently available W sources. The exchange of Majorons will contribute to these polarizations; these may provide limits on the couplings of these particles to leptons.

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I. INTRODUCTION

Planned multi-TeV, high luminosity $\bar{p}p$ colliders will be a source of a large number of $W^{\pm}$ bosons. At the CERN Large Hadron Collider (LHC) with a luminosity of 10^{34} $\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$ a cross section of 130 nb [1] yields a 1300 Hz production rate; the decay $W \to l\nu$, for any lepton, occurs 10% of the time. Because of the V-A structure of the W production vertex, low-$p_\perp$ W's come out polarized [2]. Theoretical calculations of the polarizations involving the W spin $\boldsymbol{J}$ and the transverse spin of the lepton, $\boldsymbol{s}$, at the 5×10^{-5} or even lower levels, in comparison with experimental measurements, will provide tests of (a) the standard model, (b) radiative corrections to the standard model, and (c) new physics beyond the standard model. For the latter we will look at the effects of charged doublet Majorons [3–5] on the polarizations. As we shall show, without any radiative corrections, in the case of $W^- \to \tau^-\bar{\nu}_\tau$ decay, the standard model predicts $\boldsymbol{J}\cdot\boldsymbol{s}$ polarizations around 1%; radiative corrections modify these at the 10^{-3} level with a 10% change as the mass of the Higgs boson varying between M_W and $4M_W$. These effects are larger when the lepton momentum is parallel to the quantization axis for the W spin; unfortunately, because of angular momentum conservation, the rate is very small, and vanishes in the limit $m_l \to 0$.

We shall be more interested in the triple correlation $\boldsymbol{s}\cdot\boldsymbol{J}\times\boldsymbol{Q}$, where $\boldsymbol{Q}$ is the momentum difference of the outgoing lepton and neutrino. The polarizations in this correlation are proportional to the imaginary parts of the decay amplitudes. Radiative corrections in the standard model yield polarizations at the order of 10^{-5}; however, a one-loop correction due to the exchange of charged Majorons can result in significantly larger polarizations.

In Sec. II we obtain various polarization expressions in terms of the matrix elements F and G in W decays. In Sec. III radiative corrections are evaluated to one loop, both in the standard model and the doublet Majoron model. Results are summarized in Sec. IV.

II. POLARIZATION DYNAMICS

In the case which neutrinos are left handed and massless, the most general $W^- l^- \bar{\nu}_l$ vertex has the form

$$\mathcal{M}_\mu = \bar{u}(p_l)\left(F\gamma_\mu + \frac{Gm_l}{M_W^2}Q_\mu\right)(1-\gamma_5)v(p_\nu)\,, \qquad (1)$$

where $Q = p_l - p_\nu$, and F, G are dimensionless quantities to be evaluated. To the lowest order, we have $F = g/(2\sqrt{2})$, $g = e/\sin\theta_W$, and $G = 0$. As will be shown below, the polarizations of leptons depend only on G/F; thus, the radiative corrections to F which are small can be ignored. In any case F is determined by the the rate of $W \to l^- + \bar{\nu}_l$. In addition the corrections to G are kept to the lowest order in m_l/M_W. Since this factor already appears in the definition of G in Eq. (1), m_l is set to zero except for a photon exchange diagram (to be discussed below) which has a dependence on $\ln(m_l/M_W)$.

The differential decay rate for a W at rest is

$$\frac{d\Gamma}{d\hat{\boldsymbol{Q}}} = \frac{1}{256\pi^2 M_W}\Bigg\{F^*F[-\boldsymbol{Q}\cdot\boldsymbol{\epsilon}^*\boldsymbol{Q}\cdot\boldsymbol{\epsilon} + M_W^2\boldsymbol{\epsilon}\cdot\boldsymbol{\epsilon}^* - iM_W\boldsymbol{Q}\cdot\boldsymbol{\epsilon}\times\boldsymbol{\epsilon}* + m_l\,(iQ\boldsymbol{s}\cdot\boldsymbol{\epsilon}\times\boldsymbol{\epsilon}^* + \boldsymbol{s}\cdot\boldsymbol{\epsilon}\boldsymbol{Q}\cdot\boldsymbol{\epsilon}^* + \boldsymbol{Q}\cdot\boldsymbol{\epsilon}\boldsymbol{s}\cdot\boldsymbol{\epsilon}^*)]$$
$$-\frac{FG^*m_l}{M_W}\boldsymbol{Q}\cdot\boldsymbol{\epsilon}^*\,[i\boldsymbol{Q}\cdot\boldsymbol{s}\times\boldsymbol{\epsilon} + M_W\boldsymbol{s}\cdot\boldsymbol{\epsilon}] + \frac{F^*Gm_l}{M_W}\boldsymbol{Q}\cdot\boldsymbol{\epsilon}\,[-i\boldsymbol{Q}\cdot\boldsymbol{s}\times\boldsymbol{\epsilon}^* + M_W\boldsymbol{s}\cdot\boldsymbol{\epsilon}^*]\Bigg\}\,. \qquad (2)$$

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In the above equation $\boldsymbol{s}$ is the *transverse* polarization of the lepton, and $\boldsymbol{\epsilon}$ is the W polarization vector; we have $\boldsymbol{Q}\cdot\boldsymbol{s}=0$.

Measurable quantities of interest are the following.

(i) The decay rate of W's with spin $+1$ (transversely polarized) along the $\boldsymbol{J}$ direction ($\boldsymbol{J}^2=1$):

$$\frac{d\Gamma_{J=1}}{d\hat{Q}}=\frac{F^*F}{512\pi^2 M_W}(M_W-\boldsymbol{Q}\cdot\boldsymbol{J})^2\left[1+\frac{2m_l}{M_W-\boldsymbol{Q}\cdot\boldsymbol{J}}\left(1-\mathrm{Re}\frac{G}{F}\right)\boldsymbol{s}\cdot\boldsymbol{J}-\mathrm{Im}\frac{G}{F}\frac{2m_l}{M_W(M_W-\boldsymbol{Q}\cdot\boldsymbol{J})}\boldsymbol{Q}\cdot\boldsymbol{s}\times\boldsymbol{J}\right]. \quad (3)$$

(ii) A similar quantity for a W with spin 0 (longitudinally polarized) along the $\boldsymbol{J}$ direction:

$$\frac{d\Gamma_{J=0}}{d\hat{Q}}=\frac{F^*F}{256\pi^2 M_W}\left[M_W^2-(\boldsymbol{Q}\cdot\boldsymbol{J})^2\right]\left[1+\frac{2m_l}{M_W^2-(\boldsymbol{Q}\cdot\boldsymbol{J})^2}\left(1-\mathrm{Re}\frac{G}{F}\right)\boldsymbol{Q}\cdot\boldsymbol{J}\boldsymbol{s}\cdot\boldsymbol{J}\right.$$
$$\left.-\mathrm{Im}\frac{G}{F}\frac{2m_l}{M_W[M_W^2-(\boldsymbol{Q}\cdot\boldsymbol{J})^2]}\boldsymbol{Q}\cdot\boldsymbol{J}\boldsymbol{Q}\cdot\boldsymbol{s}\times\boldsymbol{J}\right]. \quad (4)$$

The asymmetry in two polarizations is the largest when $\boldsymbol{Q}$ and $\boldsymbol{J}$ are parallel; however, angular momentum conservation forces these rates to vanish in these directions. We shall present details of the polarizations averaged over angels in the case of W spin $+1$ along the $\boldsymbol{J}$ direction. For the $\hat{\boldsymbol{s}}$ in the $\hat{\boldsymbol{Q}}$-$\hat{\boldsymbol{J}}$ plane case we find

$$\mathcal{P}_{\parallel}=\frac{3\pi m_l}{8M_W}\left(1-\mathrm{Re}\frac{G}{F}\right), \quad (5)$$

and, for the $\hat{\boldsymbol{s}}$ normal to the $\hat{\boldsymbol{Q}}$-$\hat{\boldsymbol{J}}$ plane case,

$$\mathcal{P}_{\perp}=\frac{3\pi m_l}{8M_W}\mathrm{Im}\frac{G}{F}. \quad (6)$$

Longitudinal polarized W's give a zero angular averaged transverse polarization of leptons, restricted angular averaged yield results similar to the ones above, Eq. (5) and Eq. (6).

The imaginary part of G is independent of the Higgs boson mass, and it is given by

$$\mathrm{Im}\,G=0.025\frac{g^3}{16\pi^2}. \quad (7)$$

The polarization transverse to the $\hat{\boldsymbol{Q}}$-$\hat{\boldsymbol{J}}$ plane [Eq. (6)] is

$$\mathcal{P}_{\perp}=4.5\times10^{-6}. \quad (8)$$

This is, again, too small for detectability.

III. RADIATIVE CORRECTIONS

A. Standard model radiative corrections

As may be seen from Eq. (3) and Eq. (4) radiative corrections to F are irrelevant in all the polarization expressions. Thus only radiative corrections to G should be considered. Standard-model one-loop corrections to G in Eq. (1) are presented in Fig. 1. Diagram by diagram they are ultraviolet and infrared finite. The lepton mass is set to zero in all loop calculations, except in the case of the photon exchange interaction, Fig. 1(c), which has a logarithmic dependence on the lepton mass. An overall factor of lepton mass already appearing in the coefficient of G in Eq. (1) is retained. In the case of $W\to\tau\nu$, results for the real part of G are plotted in Fig. 2. The lowest order contribution with plane polarization, Eq. (5), is $\mathcal{P}_{\parallel}=2.6\times10^{-2}$, and should be readily measurable. The standard model radiative corrections are $\sim5\times10^{-3}$ times the above values, changing by 5% as M_H varies between M_W and $4M_W$. The detection of these corrections is beyond the capabilities of the presently available W sources.

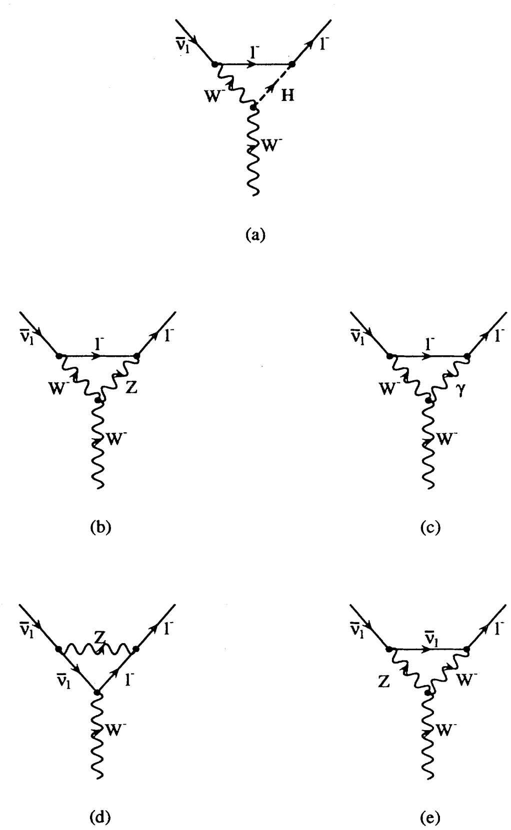

FIG. 1. One-loop corrections to the standard mode amplitude.

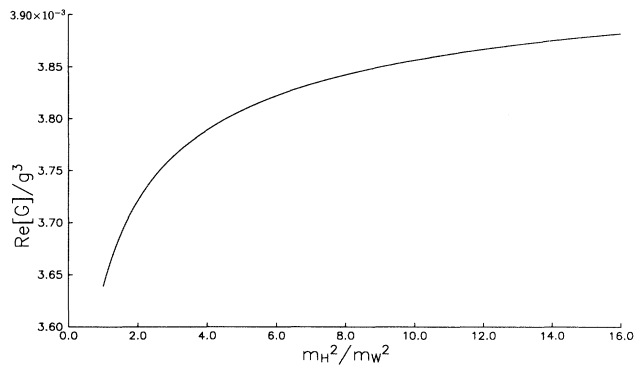

FIG. 2. Standard model contributions to the real part of the amplitude G for $W \to \tau + \nu_\tau$.

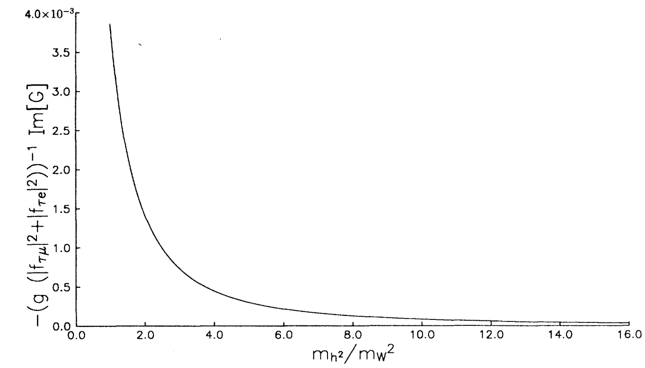

FIG. 4. Charged Majoron exchange contribution to ImG for $W \to \tau + \nu_\tau$.

The results for the muon may be obtained from those for the τ by replacing Re$G_\mu(M_H)$=Re$G_\tau(M_H) + 9.15 \times 10^{-3}$ and Im$G_\mu(M_H)$ =Im$G_\tau(M_H)$.

B. Charged Majoron exchange

The small value of ImG resulting from calculations in the standard model permits us to use it in looking for additional contributions from models beyond the standard model. In this paper, we look specifically at models which contain charged Majorons. A specific example having this property is the doublet Majoron model. It contains two charged Majorons, each carrying a lepton number equal to 2 and with masses $m_{1,2}$. As our analysis cannot separate the contributions of these two particles we shall parametrize the results in terms of one charged Majoron with an average mass m_h [4]; this mass will be assumed to be greater than M_W. The interaction vertex of interest for such a particle is

$$\mathcal{L}_{hl\nu} = f_{ab}\bar{\nu}_a^c(1-\gamma_5)l_b h^+ + \text{H.c.} \tag{9}$$

In the above, a, b label lepton families and $f_{ab} = -f_{ba}$ are, as yet, unrestricted couplings; a summation over lepton species is implied. We are interested only in the contribution to ImG due to this interaction. The Feynman diagram of the interaction is shown in Fig. 3, and the

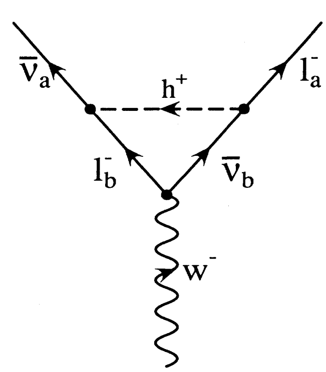

FIG. 3. Charged Majoron exchange.

calculated result is shown in Fig. 4.

Currently limits exist [4] on certain combinations of these coupling constants:

$$|f_{e\tau}f_{\mu\tau}| \le 10^{-4}\left(\frac{m_h}{M_W}\right)^2,$$
$$|f_{e\mu}|^2 \le 10^{-4}\left(\frac{m_h}{M_W}\right)^2. \tag{10}$$

These results do not rule out sizable values for either $f_{e\tau}$ or $f_{\mu\tau}$. For subsequent discussion we shall assume that it is the latter that dominates and show how polarizations in W decay can restrict this parameter.

IV. DISCUSSION

Although the standard-model one-loop corrections to G are too small to be seen with W fluxes from planned sources, $\mathcal{P}_\perp$ in Eq. (6) will be observable for a range of parameters in extended standard models that incorporate charged Majoron mesons. The transverse polarization of τ in the results shown in Fig. 4 is

$$\mathcal{P}_\perp = \left(|f_{e\tau}|^2 + |f_{\mu\tau}|^2\right) \times \begin{cases} 2.7\times10^{-4} & \text{for } m_h = M_W\,, \\ 2.4\times10^{-6} & \text{for } m_h = 4M_W\,. \end{cases} \tag{11}$$

With the polarization sensitivities discussed in Sec. I, namely, 5×10^{-5}, we find that for a charged Majoron mass close to the W's mass the out-of-plane polarization can restrict $|f_{\mu\tau}| \ge 0.4$ for $m_h \sim M_W$ and $|f_{\mu\tau}| \ge 5$ for $m_h = 4M_W$. In these models neutrino masses are [4] of the order of $m_\nu \sim m_0 f_{\mu\tau}$ with $m_0 \sim 10^{-2}$ eV. A positive result for the perpendicular polarizations would imply, within this model, $m_{\nu_\tau} \ge 4 \times 10^{-3}$ eV.

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